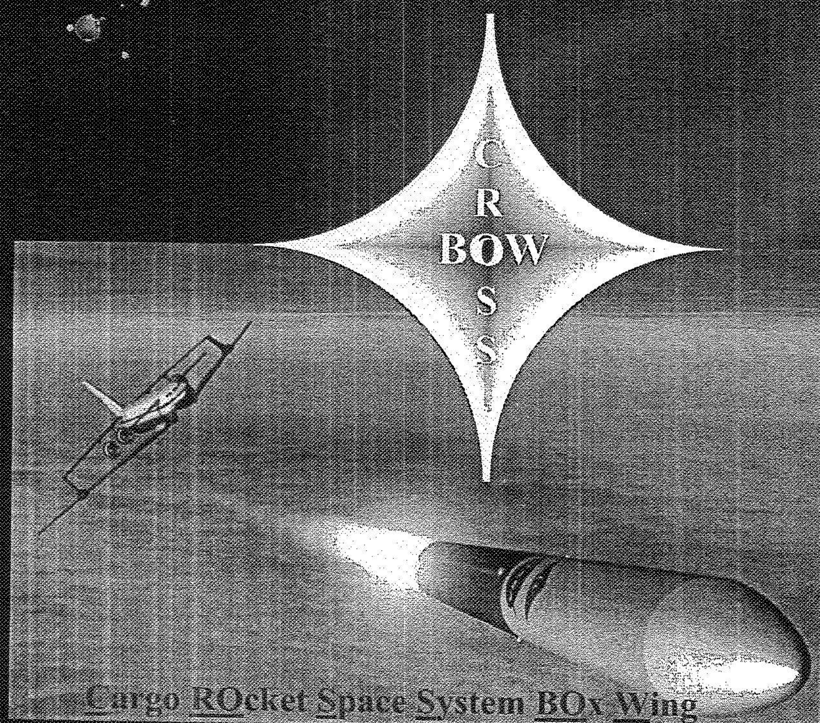
JANNAF

REUSABLE PROPULSION ARCHITECTURE FOR SUSTAINABLE LOW-COST ACCESS TO SPACE



Dr. Joseph Bonometti
Marshall Space Flight Center, MSFC, AL 35812

Kyle L. Frame
John W. Dankanich
Gray Research, Inc., Huntsville, AL 35806

December 7, 2005

How To Really Change ETO Cost?!

IN-SPACE PROPULSION

- **No one has shown conclusively how to reduce rocket launch costs.**
- **Space has never been *cost-effective*.**
- **Taking a step back and view the problem from a <u>cost</u> prespective from the very beginning:**
  - Griffin's non-architecture approach (The Cost Of Access To Space)
  - Consider safety, reliability, timeliness, etc. are 'costs'
  - Technical review of past approaches (with criticism)
  - Attack problem from ground operations where cost is highest
  - Attack problem at top of trajectory where performance is paramount
- **Keep to existing materials and technical approaches.**
- **Reprocess the *apparent best architecture* solution using Griffin's non-architecture approach.**

Don't try it the same way you did it the last dozen times you miserably failed!

Michael Griffin and William Claybaugh's 1994 cost model for space transportation

$C_T = C_h + C_p + C_o$ } Cost of expended launch vehicle hardware + launch vehicle propellant + launch site operations

$C_h = c_h\ f\ M_s$ } Specific cost of launch vehicle hardware x mass fraction of expended hardware x launch vehicle dry mass

$C_p = c_p\ M_p$ } Propellant costs

$C_o = c_L\ L\ M_s$ } Hourly rate x launch prep hours (includes refurbishments between flight + launch site preparation)

$C_T = ((c_h\ f\ R) + (c_p\ P) + (c_L\ L\ R))\ M_{PL}$ } In terms of payload mass (define R as dry-mass to payload-mass fraction and P as propellant-mass to payload-mass fraction)

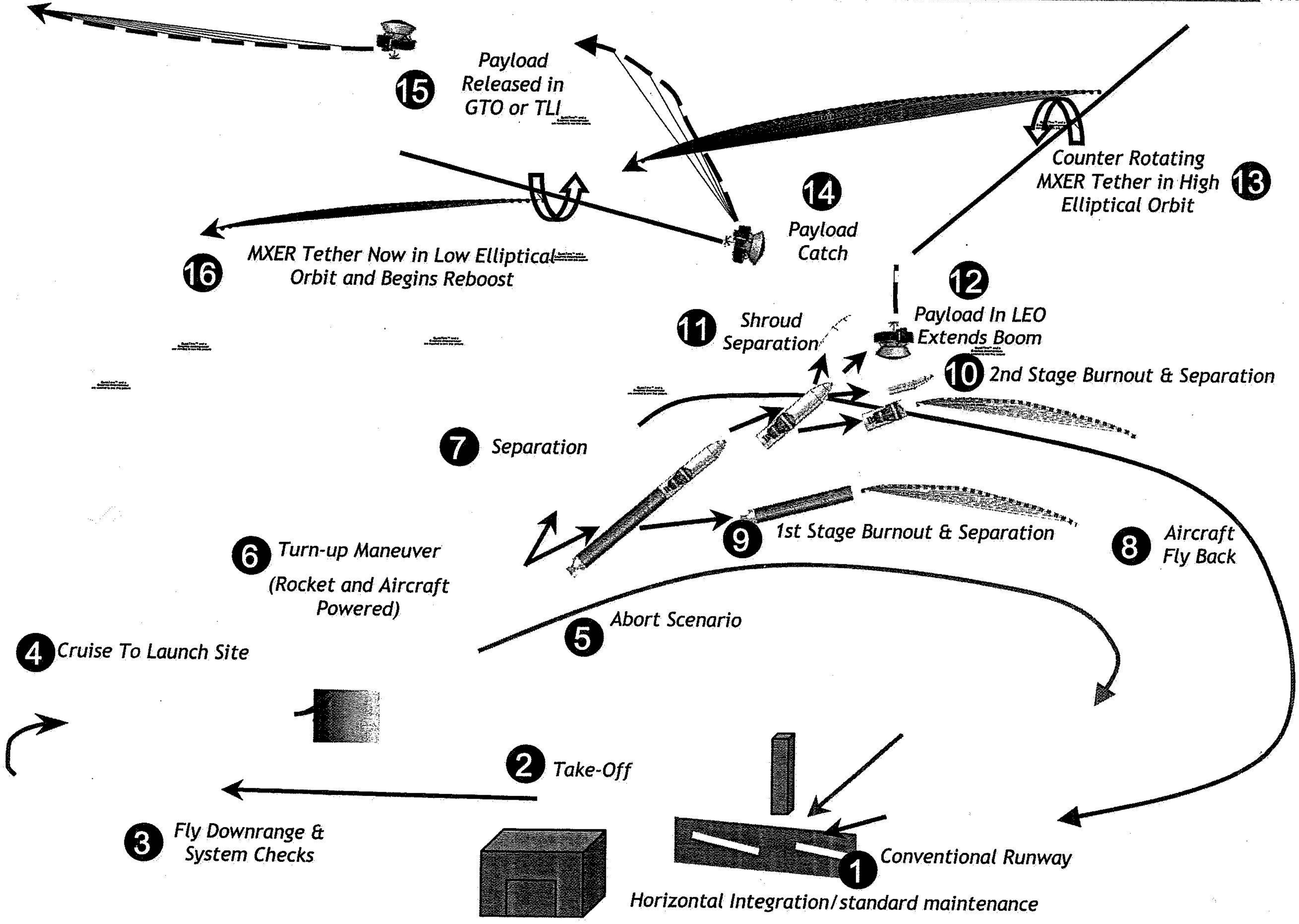
$c_T = c_h\ f\ R + c_p\ P + c_L\ L\ R$ } Specific total launch cost

Proposed Architectural *Change in Paradigm*

IN-SPACE PROPULSION

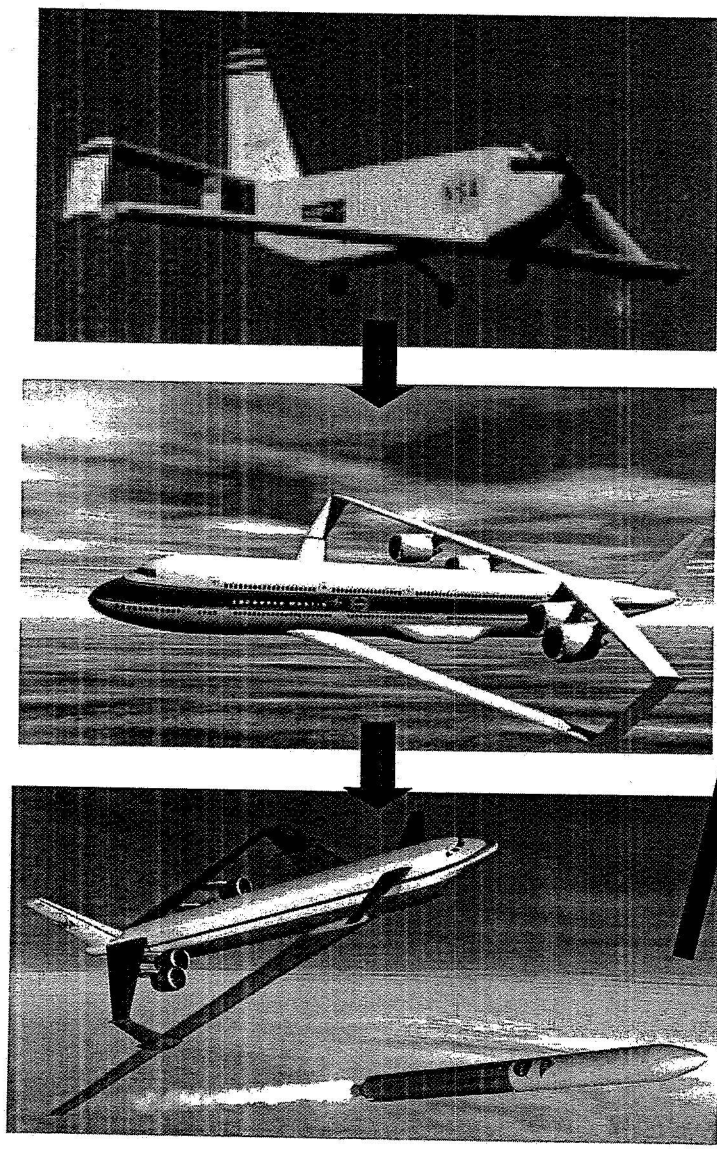
1. Subsonic aircraft in place of the rocket booster (use highest payload capacity to keep cost effective both in the aircraft and on the rocket)
2. Limit to existing runway infrastructure
3. Keep the rocket small to reduce cost
4. Performance requires LOX/LH2 at the top of the trajectory (so limit it to the one engine type - Expander Cycle- as a compromise between performance and cost)
5. Offload as much delta-v at the top of the trajectory and exponentially reduce rocket size as well as aircraft size with a reusable tether system

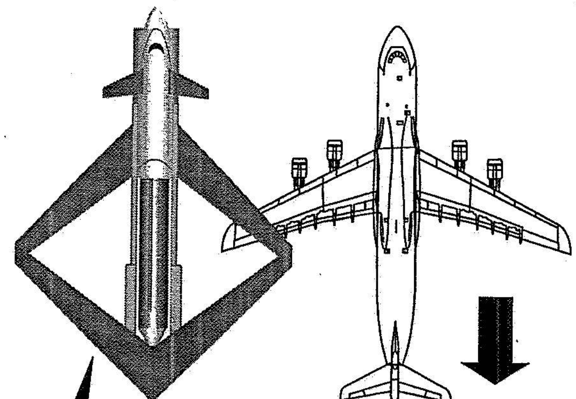
ETO Architecture Launch Sequence



CROSSBOW

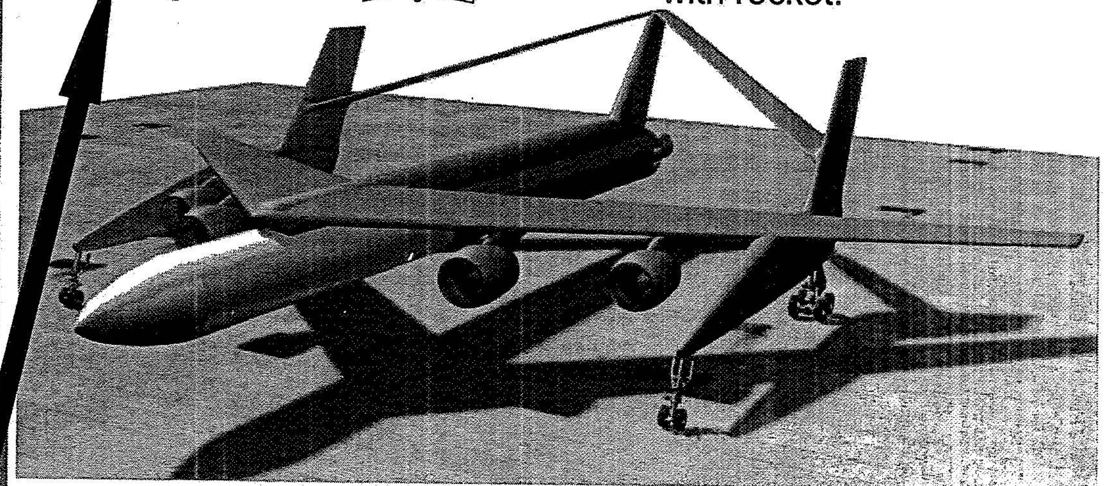
(Cargo ROcket Space System BOx Wing)





Key Features:

- Subsonic
- Limited by existing runways
- Designed for alternate missions
- Pod-hauler design
- Unmodified commercial engines
- Does the turn-up maneuver with rocket!

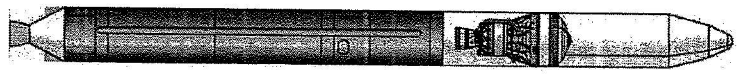


Military Transport

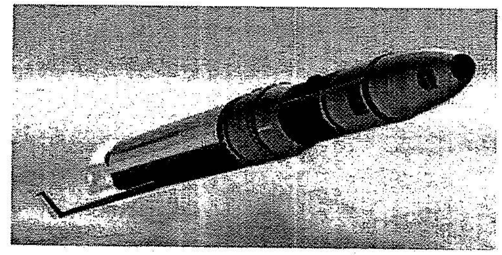
Civilian Pod-Hauler

Rocket System

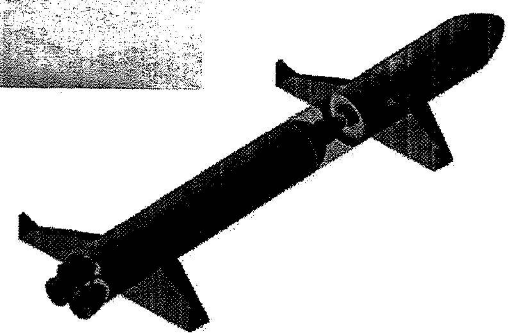
Modified Delta IV with 3 RLX engines on core and 1 RLX on upper stage



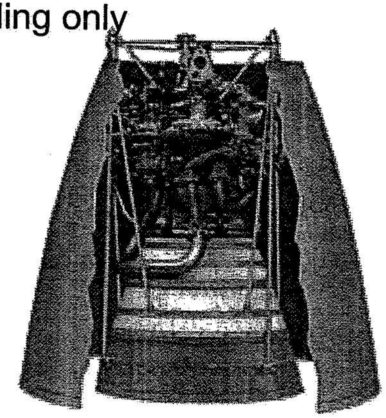
Reusable LH2/LOX first stage with 3 RLX engines and Delta 4 upper stage with 1 RLX engine



Reusable LH2/LOX first stage with 3 RLX engines and reusable winged second stage with 1 RLX engine



Key Features:
- 2-Stages
- All LOX/LH2
- Same engines on both stages
- Wings/landing gear (if any) are sized for empty weight landing only



250 klb Expander Cycle	250 klb EX
Chamber pressure	**~1500 psi**
Expansion ratio	**75**
Mixture ratio	**6.0**
Development costs	**Low**
Development risk	**Low**
Vacuum I_{sp}	451 sec
Altitude I_{sp} (1/4 atm)	408 sec
Sea-level I_{sp}	278 sec

MXER Tether

IN-SPACE PROPULSION

QuickTime™ and a
DV/DVCPRO - NTSC decompressor
are needed to see this picture.

Cost Analysis Assumptions

- Make conservative assumptions:
  - **Cost of labor is assumed at an average of $150,000 per man-year (average labor mix)**
  - **Cost of propellant is assumed to remain constant at $2/kg**
  - **Cost of Transportation Devices:**

	c_h	Quantity Produced
Rockets	$2500 / kg	10 Š 100
Airplanes	$1000 / kg	100 Š 1000
Cars	$3 -$5 / kg	10,000 Š 100,000

  - **Complexity of aircraft and rockets in terms of hardware, avionics, and manufacturing quality control are both on the same order, but mass production even on the order of a few hundred has substantial cost savings (more than doubling the price between a Ferrari and a true Formula 1 race car)**
- **Operations cost of MXER is unknown, but conservatively assumed to be two orders-of-magnitude higher than other TLI systems operations cost.**

Cost Analysis Approach Modification

For air launch cost each stage separately:

$C_T = C_T$ 1st Stage + C_T 2nd Stage =

$$[c_p M_P + c_L\, L] + [(c_h\, f\, R) + (c_p\, P) + (c_L\, L\, R)]\, M_{PL}$$

(Note as with the booster, there are development and purchase costs associated with an aircraft)

"The aircraft is not expended, which should lead to a reduced launch cost by decreasing the expended fraction, "f". This is the cost model that clearly shows the significant benefits of a reusable single stage to orbit (SSTO). For an air launch system the model should be implemented in stages because the dry mass of an aircraft is very large compared to that of a first stage rocket casing or tankage/engines. This may only be a trivial and intuitive modification, but without it, one could simply reduce launch costs by adding weight to the aircraft."

$$f \equiv \frac{ExpendedHardware}{TotalHardware} \qquad \lim_{M_{aircraft}\to\infty} \frac{M_{Expended}}{M_{Expended} + M_{aircraft}} = 0$$

General Design Data

Air launch

- Launch conditions ~10km (~35,000 feet)
- Mach ~0.75 and a high gamma angle (~45 degrees) at separation
- 500,000 kg GLOW
- All subsonic operations using unmodified GE90 class engines
- Conventional aluminum airframe construction

Momentum Tether

- (Zylon tether material (safety factor of 3 in a braided Hoyt structure)
- Minimum 60-day reboost time between uses (nominal 30-day practical limit)
- 2500 kg payload thrown to TLI and a 10:1 tether to payload ratio
- Single launch (i.e., Delta IV Heavy or Sea-Launch)
- Upper stage booster as ballast or counter-mass not assumed
- ElectroDynamic (ED) reboost system consists of flywheels, solar panels aluminum wire carried by a Zylon strength-tether
- System length is on the order of 100 kilometers
- Flight rate of 6 tosses per year (assessment ranged from 1 to 52)

Summary of First Stage Characteristics

	Expended Hardware (kg)	Total Hardware (kg)	Dry Mass (kg)	Max (min*) Propellant Mass (kg)	Max Payload Mass (kg) To 10 km	GLOW (kg)	Cost (Millions)
Shuttle Solid Rocket Motor	88,000	88,000	88,000	502,000	[redacted]	1,365,000††	[redacted]
Delta IV 1st Stage	26,701	26,760	26,760	199,600	475,000†	701,400††	~$75*
Boeing 777-200 (Commercial)	0	145,149	167,829	145,541 (20,000)	157,218**	345,047	$140
Boeing 747-400 (Commercial)	0	179,015	179,015	164,064 (20,000)	163,859**	362,874	$225
Russian Antonov-225	0	285,000	285,000	300,000 (65,000)	250,000	600,000	$300
Air Launch (Crossbow)	0	230,000***	230,000***	(15,000)	[redacted]	500,000*	[redacted]

Note worst case: Plane must be used is 9 times to "break even"

* Estimated value for air launch case.
** Calculated by subtracting the min propellant mass and dry mass from the GLOW.
*** Calculated by subtracting the max payload mass (230,000 kg 2–stage rocket & 25,000 kg spacecraft payload) and max aircraft propellant mass from the GLOW.

† Determined from the rocket equation, using 1200 m/s delta-v to 10 km altitude.

†† Sum of the payload, dry mass and propellant.

Summary of Launch Vehicle Parameters

IN-SPACE PROPULSION

	f	P	R
Air-Launch (Crossbow)	0**	0.06 (NA)	9.2(NA)
[redacted]	1	[redacted]	[redacted]
	1		
Shuttle*	0.2 Š 0.3	81	14.3
Chemical TLI Engine	1	5	0.5

f - Mass fraction of hardware expended

P - Ratio of propellant mass to payload mass M_P / M_{PL}

R - Ratio of dry mass to payload mass M_S / M_{PL}

Note bigger Is not always better for rockets!

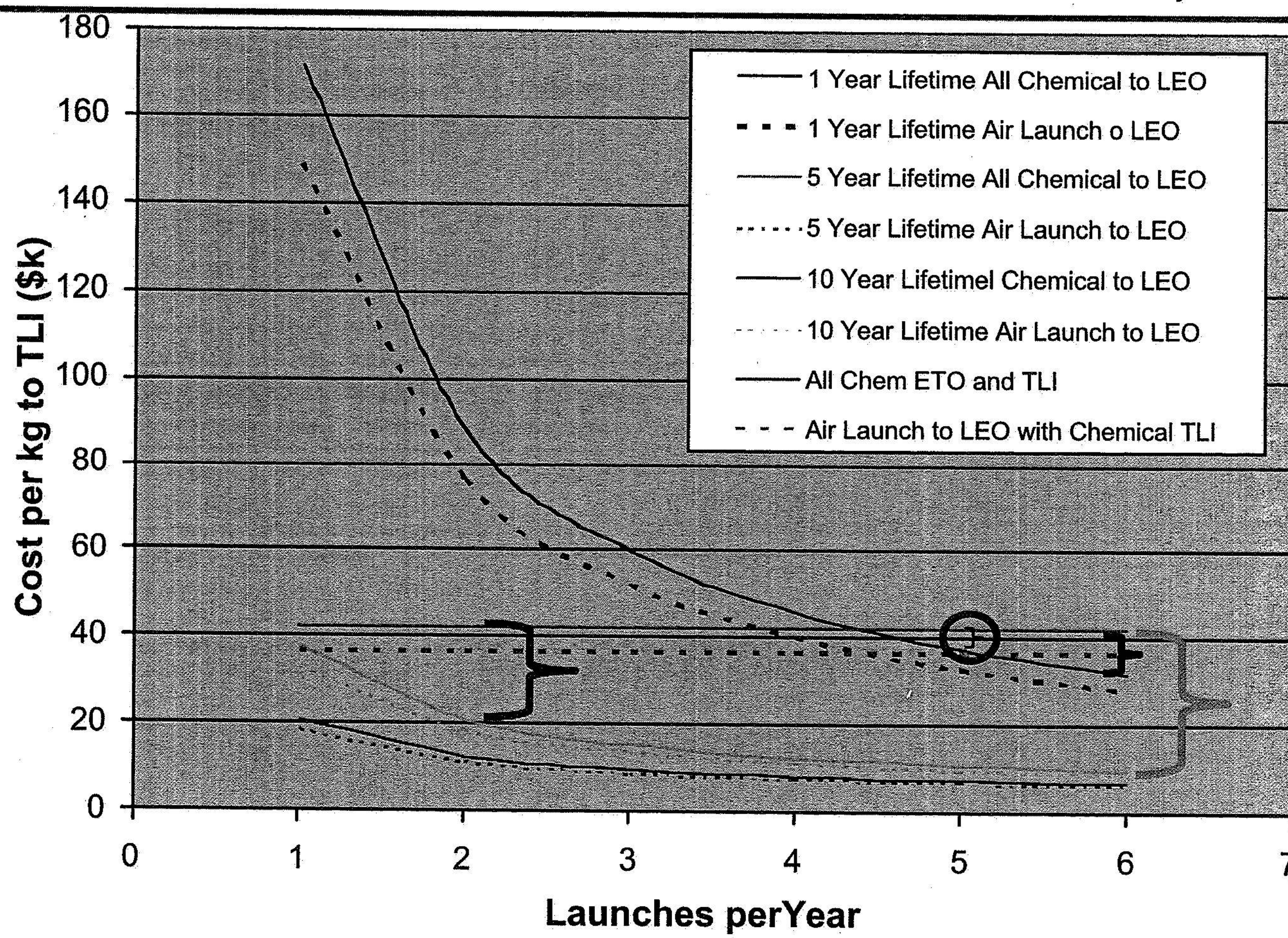
Cost of Payload to LEO

	Baseline Cost per kg of Payload to LEO (Per lb)
All Chemical ETO	\$16,800 (\$7,650)
Air Launch with L_{ox}/L_{H2} Orbit Injection	\$14,500 (\$6,600)
Effective Cost to LEO Using MXER*	\$450 (\$200)

Cost savings trend of ~10% for the air launch case.

Major cost reduction for the tether case.

Comparison of cost per kilogram of payload mass to TLI (chemical injection stage versus MXER)



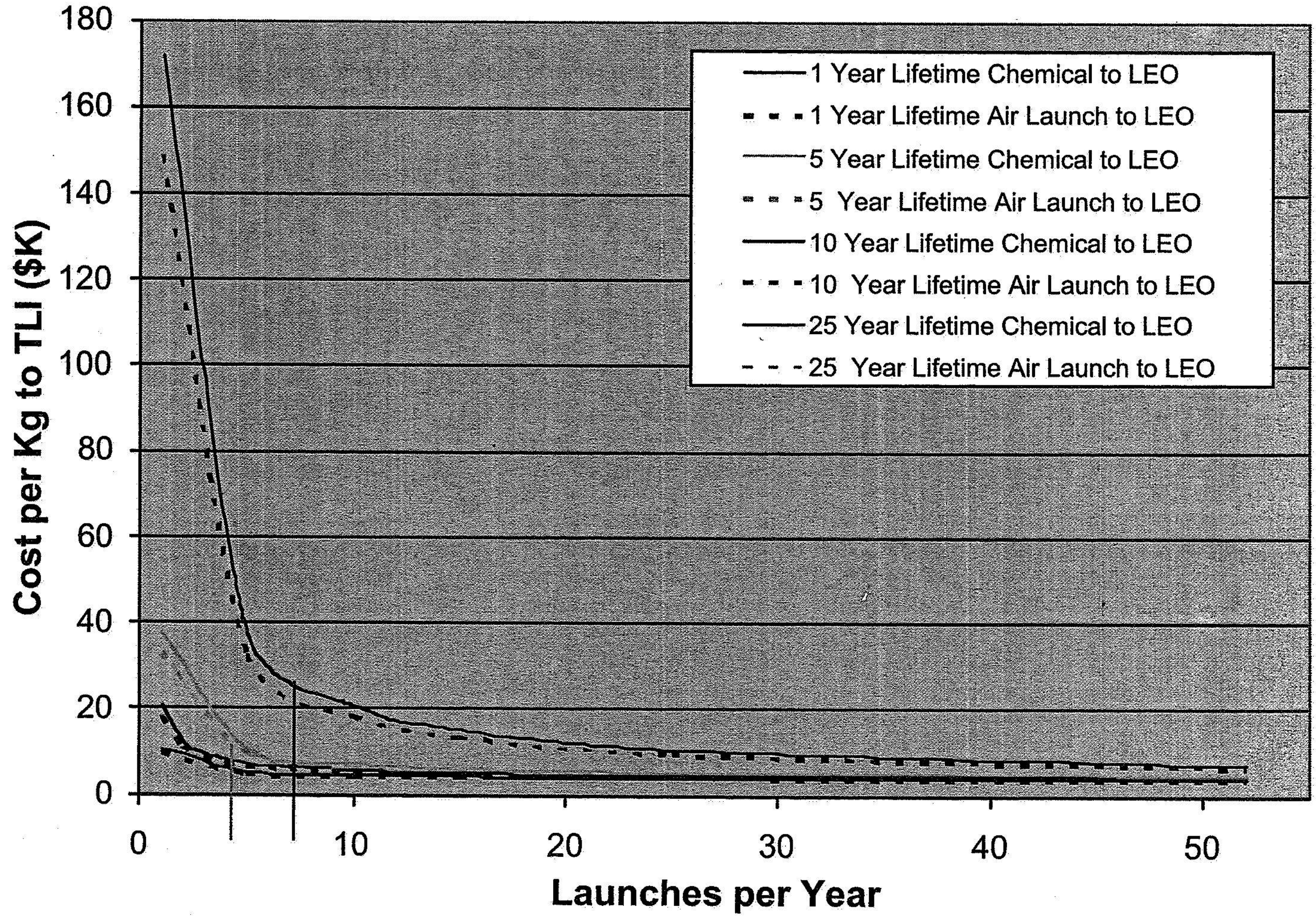
A 5-year tether lifetime, with 2 launches a year, reduces the cost by ~50%

Minimum of 5 uses to "breakeven" with the all-chemical lunar mission

(10% to 15% savings for 1-year tether with each additional use)

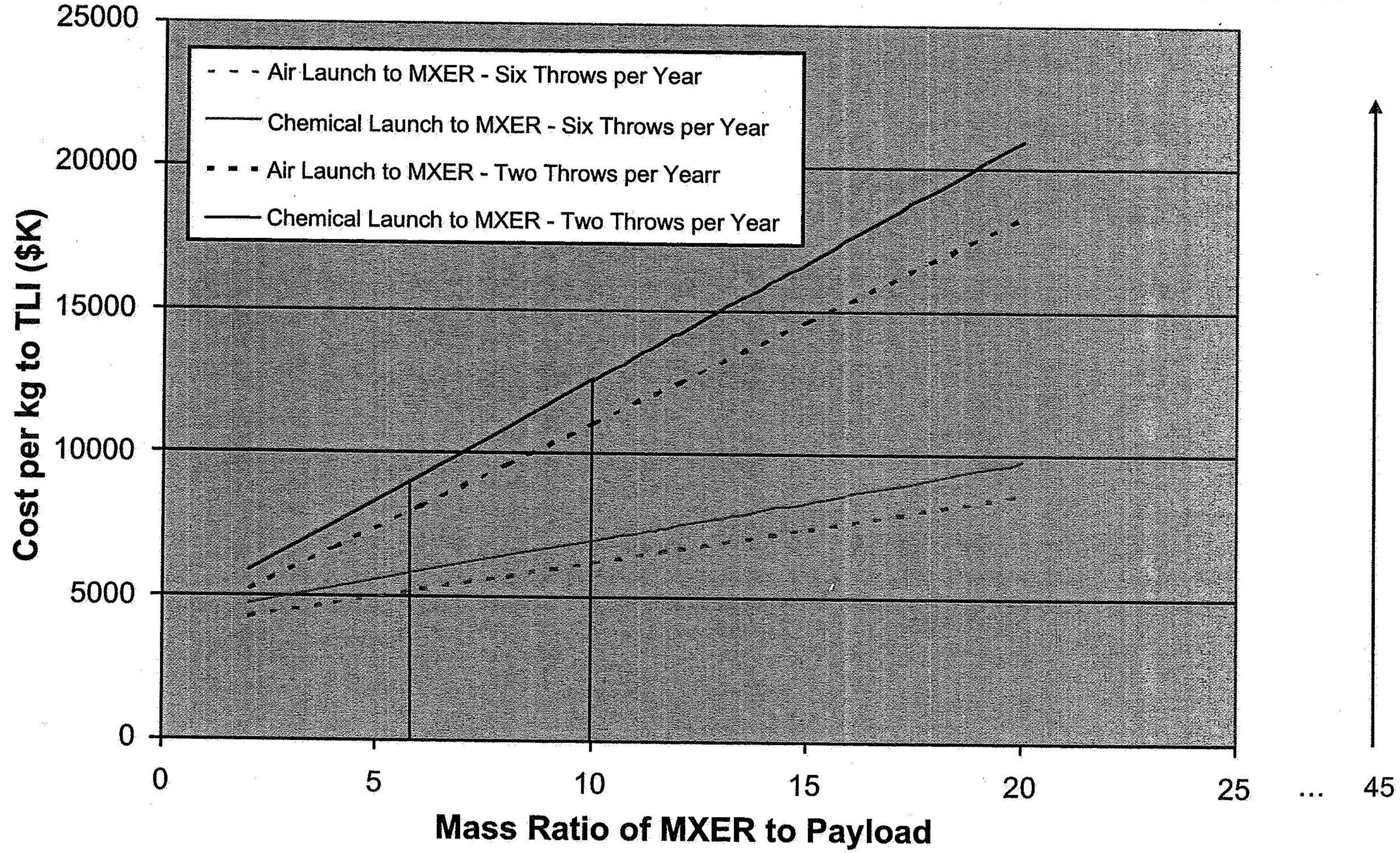
5 and 10-year lifetime tethers reduce the cost from 50% to 75%

MXER Lifetime Effect
(cost of payload mass to TLI)



Substantial cost reductions are seen early, therefore lower risk to achieving the architecture's minimum goals.

MXER Mass Ratio Effect
(cost to TLI assuming no on-orbit assembly)

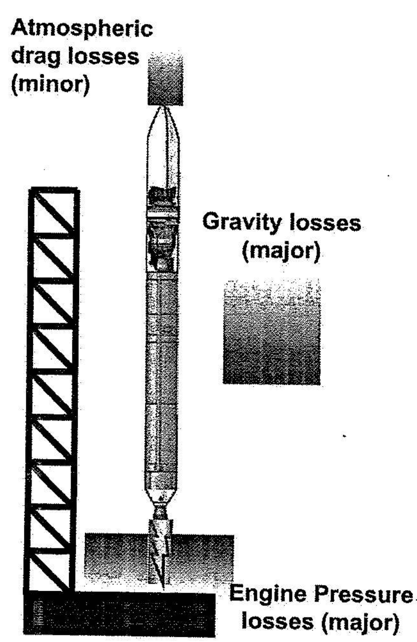


The MXER to Payload Mass Ratio can be as large as 45:1 for "breakeven", if used for 10 years (low end has been projected at 6:1, but study used 10:1).

Air Launch Non-Cost Benefits
(real-world added costs)

- Flight delays due to weather
- Safety and abort scenarios
- Insurance premiums when there is no possible recovery
- A loss-of-vehicle accident (implications of recovery, investigation and return-to-flight processes)
- Many aircraft in operations (significant factor identifying and correcting anomalies)
- Available parts at commercial prices
- Flexibility in trajectory selection, independent of launch site
- Same launch and return (or abort) site by flying downrange first
- Dual-use for military and cargo transport
- Changes to airline industry and security
- Architecture's perception or human appeal (believable by the average person)

Classical Rocket Benefits



- **The attractive attributes of limited rocket size (i.e., Delta IV Heavy or Atlas V class payload using a Delta-IV) include:**
  - Vehicle price to be within reach of 'other' customers
  - Normal size manufacturing, shipping & inspection
  - Lower development costs & risk
  - Less infrastructure (i.e., cryogenic fuel storage, building space, cranes, etc.)
- **Limited payload size attractive attributes include:**
  - Automatically generates higher flight rate
  - Keeps insurance low for individual payloads
  - Single payload flexibility and convenience
- **Rocket designed to start at ~35,000 feet:**
  - Minimizes dynamic Max-Q
  - Almost eliminates drag losses and engine pressure losses
  - Reduces gravity losses

Conclusions

- **Two transportation architecture changes are presented at either end of a conventional two-stage rocket flight**
    - Air launch using a large, conventional, pod hauler design (i.e., Crossbow)
    - Momentum exchange tether (i.e., an in-space asset like MXER)
- **Air launch has an analytically justified cost reduction of ~10%, but its intangible benefits suggest real-world operations cost reductions much higher:**
    - Inherent launch safety
    - Mission risk reduction
    - Schedule enhancement
    - Favorable payload/rocket limitations
    - Leveraging the aircraft for other uses (military transport, commercial cargo, public outreach activities, etc.)
- **For payloads delivered beyond LEO, the most effective method of reducing ETO costs may not be in the ETO vehicle, but rather by increasing the ratio of useful payload to mass delivered into LEO**
- **Momentum exchange tethers have upwards of a 50% cost reduction for ETO and can operate deep in the Earth's gravity well**
- **Both systems work to enhance conventional rocket technology without reaching for exotic or risky materials or methods**
- **Changing the existing ETO rocket paradigm takes these two architectural alterations to make space flight sustainable and affordable, particularly for lunar operations**